"From Pilot's Associate to Satellite Controller's Associate"

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Introduction

Associate Technology is an emerging engineering discipline wherein intelligent automation can significantly augment the performance of man-machine systems. An associate system is one that monitors operator activity and adapts its operational behavior accordingly. Associate technology is most effectively applied when mapped into management of the human-machine interface and display-control loop in typical manned systems. Fundamental to an associate system is an embedded operator model with which operator activity is compared. Inferences can be made about the state of the operator, and the system can respond in different ways dependent upon both the external situation and the local requirements of the operator. These technologies are being developed under the auspices of the DARPA Pilot's Associate (PA) Program.

One logical exploitation and application of associate technology is for intelligent command and control of remote assets, particularly for satellite systems. Such a system might be a satellite controller's associate, comprised of a community of coupled software processes embedded in the satellite control facilities computers. These processes would digest external world knowledge through sensed data fusion and correlation and generate inferences based on models of expected behavior for the real world. The processes would generate action plans for the operator to satisfy his goals and constraints as he continuously interacts with the external and internal environment. The processes would abide by the paradigm that the operator is always in charge, and that the data must always go through. The processes would act as decision aiding tools, incorporating display management, situation assessment and mission planning. These capabilities are all incremental evolutions of the techniques developed under the Pilot's Associate program.

This paper addresses the potential for application of associate technology into the arena of intelligent command and control of satellite systems, from diagnosis of onboard and onground of satellite systems fault conditions, to execution of nominal satellite control functions. Rather than specifying a specific solution, this paper draws parallels between the Pilot's Associate concept and the domain of satellite control.

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Program Objectives

The forerunning program, the Pilot's Associate, started with the nearly irreducible minimum crew size of one pilot in a fighter aircraft. The objective of the PA was to improve the performance of the less experienced pilots by the addition of a "virtual crew member" which could address some of the information processing limitations of the human. In part, this can be described by the threshold of performance expectation across the spectrum of operator or pilot experience. These limitations, as described by the McDonnell Aircraft PA team [Reference 1], included working memory, speed of cognitive operations, reliable retrieval of information, accuracy of numerical operations, and projection of position in time and space. These are all areas where computers excel in aiding human performance. To surmount these limitations, the PA was designed to perform internal and external situation assessment, long-range and reactive planning based on those assessments, and intelligent communication with the pilot. These functions serve to improve the situation awareness and decision making of all
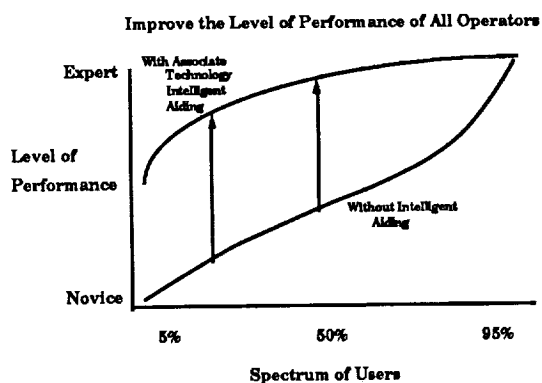

Figure 1--Human Performance Goals

operators, with respectively more payoff for the less experienced pilots.

The top level goal is to improve the performance of the entire population and thereby obtain aggregate force effectiveness improvements (Figure 1-- Human Performance Goals).

A satellite controller's associate program might have a much different objective; that being to increase effectiveness with dwindling manpower resources. It is always interesting to the uninitiated to observe the complexity and manpower intensity for monitoring, maintaining, and operating satellite systems. Currently, over 4000 personnel are necessary to man the Air Force Satellite Control Network to operate approximately 80 satellites. Predictions suggest that 135 satellites will be in place by the year 2000, and 150 will be in orbit by 2015 -- not including any added by the Strategic Defense Initiative. The number of complex satellite systems doubles, yet the number of personnel available to operate them is likely to remain constant or decrease. The use of machine intelligence to augment the abilities of satellite controllers can improve their operational effectiveness.

The incorporation of decision aiding systems can be described at three levels. Automation, at the lowest level of machine control, removes human interaction except for certain specific activities, but relies entirely on a prior knowledge and planning to adequately respond to a rigorously predefined environment (Figure 2 -- Human-Machine Interaction). Assistant systems provide sophisticated computer mechanization to allow a human operator to manipulate and manage complex information and actions upon specific operator request along the lines of traditional expert systems. Associate systems encompass the virtues of automated and assistant systems, but
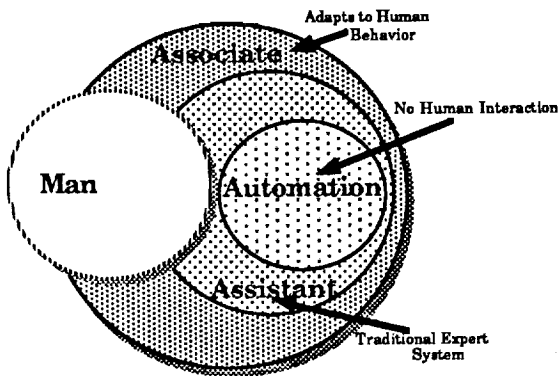
Figure 2 -- Human-Machine Interaction

add a level of internal and external environment awareness and monitoring that enables machine adaptation to both environmental constraints and human behavior in-the-loop.

Automation of routine spacecraft operations, stationkeeping, commanding and maintenance tasks has long been considered and implemented to varying degrees as a method of enhancing controller efficiency and effectiveness. In general, however, discrete task automation by itself may be insufficient and indeed undesirable, with its potential to produce unintended scripted results counter to the critical nature of many tasks.

Ten years ago four major policy goals of automation were identified to improve performance of space missions [Reference 2]. Those were:

1) Ground interaction reduction,
2) Spacecraft integrity maintenance,
3) Autonomous features transparency,
4) Onboard resource management.

To achieve these goals, levels of autonomy were identified from 0 through 10, ranging from an open-loop, non-redundant, ground-controlled onboard system, to a fully autonomous system capable of

internal reorganization and dynamic task deduction based upon unknown and unanticipated changes in the environment [Reference 3]. The trend over the past ten years has been to varying degrees an increase in the autonomy of the space segment and reduction of dependency on the ground segment. A low risk approach to reduce the reliance on manned ground control systems could be the incorporation of intelligent decision aiding. Many of the routine tasks eventually to be delegated to satellite ownership can be implemented and validated within an intelligent ground control system.

Within the bounds of the autonomy spectrum, it is possible to visualize a continuum of transfer of workload from the human operators into the domain of machine control, *within the ground control facility.* With increasing satellite autonomy, respective operator intervention, action and workload logically decrease. This is a workload baseline. From that
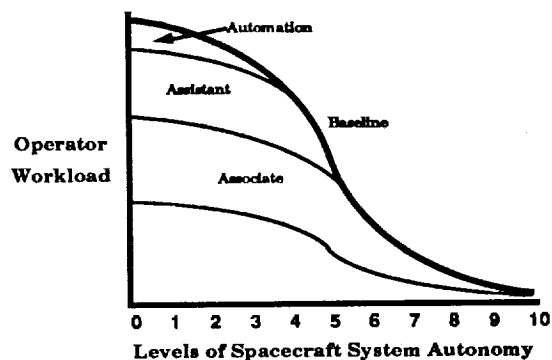

Figure 3 -- Workload Reductions

baseline, automation of ground operations tasks further reduces workload, but only for those functions not already within the autonomy domain (Figure 3 -- Workload Reductions). Assistant systems can provide additional workload reduction, but again only partially throughout the

systems or automatic transmission of command string sequences. The associate concept adds the sensed and observed feedback of operator performance to tailor the output of the associate to support the best estimate of the operator's needs at the time.

The fundamental interaction between the operator and the associate is through the approval of plans. The associate generates plans which tend to satisfy the pre-established goals of the operator (Figure 5 -- Planning Flow). If the operator rejects a plan,
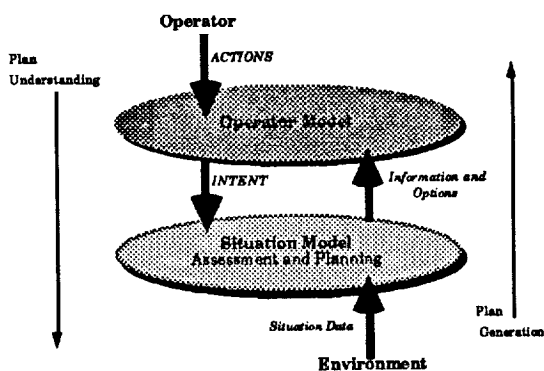

Figure 5 -- Planning Flow

for whatever reason, the next most reasonable plan is proposed. The operator can accept plans either explicitly by manual consent action or implicitly by following the course of action suggested by the plan. This is an intrinsic element of associate technology architectures. Response is governed by the philosophical construct that the operator is always in command. Paramount is the notion that the workload reduction provided by the associate system must be greater than the effort required to control the associate system. These precepts are embodied below:

1)	The operator may perform any action at any time and may override any associate system proposal or action.
2)	All potential associate system actions are considered only as proposed plans until the operator approves them.

3)	The authority given the associate system to perform actions can be controlled by the operator.
4)	The requirement that the associate system notify the operator of key mission events and associate system actions can be controlled by the operator.
5)	The plans proposed by the associate system can be preselected, weighted and tailored prior to the mission.
6)	The plans proposed by the associate system must accommodate explicit or implicit acceptance or rejection.
7)	The associate system must always behave in a well understood, predictable manner.
8)	All associate system actions must be tailorable by the operator.
9)	The associate system must monitor and adapt to operator activity, not vice versa.
10)	The associate system must follow the operator's lead.

Technology Transfer

The transferable technology from the DARPA PA program falls into two major categories: the software development process for integration of complex knowledge-based software systems and the inherent commonality of the underlying associate system architecture with its respective development environment.

The software development process began as the crafting of conventional expert systems. The well-known artificial intelligence shells and the foundation Lisp language were used to provide the system functionality, but these constructs suffered from lackluster real-time performance. The PA system matured into a hybrid system with a preponderance of the software better described as procedural than as declarative. Major embedded functions, such as route optimization and subsystem performance models, were used in their native form and language. As the program impetus to achieve real-time performance grew, the need to use the more efficient languages of C and C++ became

apparent. In retrospect, the artificial intelligence environment was found to very useful in defining requirements and developing functionality using rapid prototyping. As the system evolved to a more deterministic nature, conventional software development procedures become more appropriate.

The PA program is generating a substantial experience base in adapting intelligent software to standard hardware environments. The experience of the program since January 1990 has been oriented toward moving the five cooperating expert systems and the ancillary support functions from the Lisp laboratory environment to a "brassboard" avionics environment. In the case of McDonnell Aircraft, the Phase I environment consisted of TI Explorer machines linked to the avionics displays of an aircraft research flight simulator. For Lockheed, the Phase I environment consisted of Symbolics machines and a Micro-VAX driving a specially built cockpit. The Phase II Lockheed environment consists of RISC processors hosted in a VME chassis and using the VxWorks operating system. The resulting system provides data flow similar to what one would expect in a federated architecture avionics system (Figure 6 - Pilot's Associate Data Flow).

The PA program has adapted the MIL-STD-2167A software development standard to accommodate a rapid prototyping development cycle. As a research-oriented endeavor, the program capitalized on the merits of rapid prototyping. The rapid prototyping process includes both the definition and refinement of requirements and the incremental coding, integration, and testing of functionality. This iterative process is not readily supported by the MIL-STD 2167A prescribed process. As a result, the documentation process reflects software "as built" with performance specifications evolved during development. The implication of this software management approach is that close involvement of the technical management team is essential to ensure that the directions and results match the intent and goals of the overall program.

Knowledge Engineering

The knowledge base of the Lockheed Pilot's Associate is described with a Plan-Goal graph. The top-level goals are expressed as COMPLETE-MISSION, PERFORM-MISSION-ROLE, RETURN-GOOD-AIRCRAFT, and SURVIVE. Various plans support the achievement of these goals. A similar structure might be developed for a Spacecraft Controller's Associate knowledge base. Here the top-level goals might be COMPLETE-OPERATIONAL-TASK and ASSURE-OPERATIONAL-LIFETIME. Plans which have sub-goals addressing each of the operational sub-tasks for the system would support one or the other of the top-level goals.
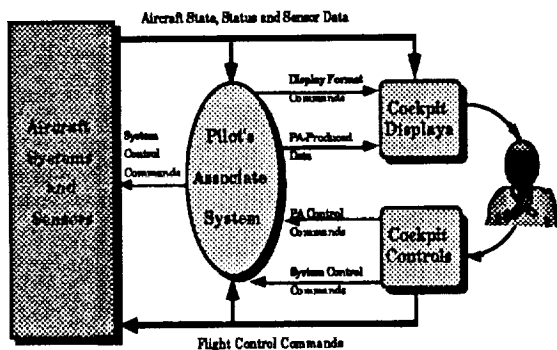

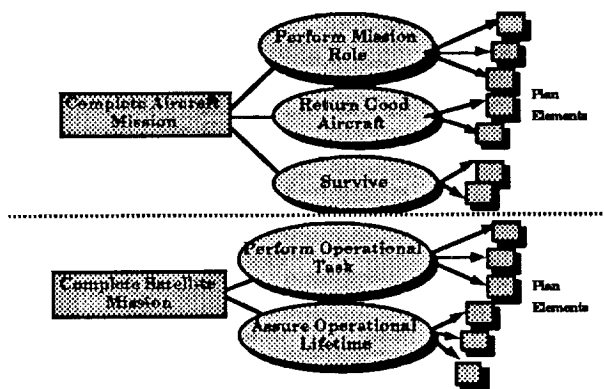Figure 6 - Pilot's Associate Data Flow

Figure 7 -- Plan Goal Graph

The organization of system operational knowledge into a plan goal graph provides a ready method for the resolution of conflicts. Where goals conflict, there will always be a higher level goal with some relative importance attached. The relative importance of conflicting goals is dependent upon the current situation and context. These elements
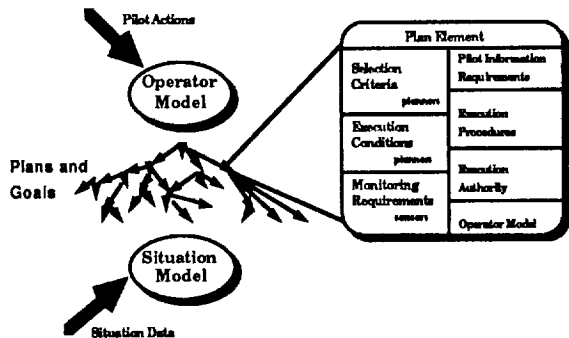

Figure 8 -- Plan Elements

are utilized within the PA as the basis for conflict resolution. Each node in the Plan Goal Graph is considered a planning object, containing sufficient detail to enable plan generation and plan understanding (Figure 8 -- Plan Elements). The same mechanism could be used to resolve the conflicts that might arise in operational control of a satellite, such as orbit adjustment conflicting with attitude control fuel usage.

The PA is designed along parallel consideration of immediate, reactive planning and long-term, mission optimization. These considerations are explicitly represented in the tactics planner and the mission planner. The plans produced by these two planners make use of system resources (for which the current state is maintained by the system status sub-system) and current situation information (for which the current state is maintained by the situation assessment sub-system). Because a satellite controllers associate would not be constrained to supporting a single operator, the planning function might be divided along the lines of operations and maintenance, rather than tactics and mission. The single pilot-vehicle interface of the PA might also be replaced by specialized intelligent interface units tailored for the specific function of each individual control position.

Associate Technology Trends

The inaugural associate program has been the DARPA Pilot's Associate program. Begun in 1986, the PA was designed as a military application within the parent Strategic Computing Program with the objective of integrating real-time, cooperating expert systems. The mechanisms for communication and cooperation between the expert systems are now well proven. Designing and building expert systems for real time operation is on track for demonstration in early 1992.

DARPA has also pursued a Submarine Operational Automation System (SOAS) which draws upon the decision aiding concepts of the Pilot's Associate. The SOAS supports tactical and mission planning with specifics

in signature management, resource management, damage control, and weapon planning. The SOAS provides this support to the skipper and battle staff of an attack submarine, addressing the issues of hierarchical planning and multi-agent reasoning.

The Army Aviation Systems Command (AVSCOM) has followed DARPA with the establishment of a Rotorcraft Pilot's Associate program. Like the DARPA-Air Force PA, the RPA program emphasizes cognitive decision aiding. AVSCOM has chosen a limited mission area for initial development and flight demonstration, that being cognitive support during a day or night, adverse weather pilotage mission. This mission can be equated to an under-the-weather, survivable, infiltration/exfiltration helicopter flight mission. This program is one year into a two-year preliminary design phase involving early determination of specific measures of effectiveness.

Conclusion

Both the design philosophy and the architecture of the Pilot's Associate system are sufficiently general to permit fairly direct application to other decision aiding environments. The packaging and throughput requirements of the fighter aircraft application were very restrictive. Achieving complex, computer-aided decision support for applications where volume, weight and power constraints are less severe provides opportunity for growth and enhancement. It would seem that the time is appropriate to consider this advanced form of operator decision aiding in the context of space mission operational requirements: a Satellite Controller's Associate.

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